Investigation of nZEB social housing built to the Passive House standard

Colclough, S., Kinnane, O., Hewitt, N. J., & Griffiths, P. (2018). Investigation of nZEB social housing built to the Passive House standard. *Energy and Buildings*, *179*, 344-359. https://doi.org/10.1016/j.enbuild.2018.06.069

Published in:
Energy and Buildings

Publication Status:
Published (in print/issue): 15/11/2018

DOI:
10.1016/j.enbuild.2018.06.069

Document Version
Author Accepted version

INVESTIGATION OF nZEB SOCIAL HOUSING BUILT TO THE PASSIVE HOUSE STANDARD

Shane Colclough[1*]; Oliver Kinnane[2]; Neil Hewitt[1], Philip Griffiths[1]

1: Centre for Sustainable Technologies, Ulster University, Shore Road, Newtownabbey, BT37 0QB, UK

2: School of Architecture, Planning and Environmental Policy, Richview Research, University College Dublin, Ireland.

Corresponding Author. Email S.Colclough@ulster.ac.uk

Highlights

- The Passive House (PH) Standard is shown to facilitate nZEB implementation.
- nZEB houses can be constructed at no extra cost over traditionally built dwellings.
- The IEQ of the monitored PH outperform current building regulations dwellings.
- The nZEB/PH exhibits low heating costs and high occupant satisfaction.
- Overheating needs to be addressed through design and operation

Abstract

Across Europe dwellings will be constructed to comply with nearly Zero Energy Buildings (nZEB) standards by 2020. This requires highly performing dwellings, an arena previously the preserve of the Passive House (PH) Standard. This study examines the operational performance and cost of a set of nZEB dwellings built as PH dwellings and thereby investigates the potential of the PH typology as a solution to nZEB. This investigation is undertaken with particular focus on the context of social housing, given that this will account for a considerable portion (c.40%) of housebuilding in the next 10 years within some EU jurisdictions.

Detailed construction cost comparisons are presented for an nZEB compliant PH dwelling (which is part of a scheme of 12 such dwellings) and compared to a similar dwelling which is constructed to comply with the current building regulations in the Republic of Ireland. The Indoor Environmental (I.E.Q.) conditions, energy consumption and monitored cost of heating and ventilation are also presented. In addition, the paper presents the results of a comprehensive occupant satisfaction survey and extensive post occupancy monitoring and analysis for the scheme of PH dwellings. Finally it compares the monitored performance with that of 20 "standard" and PH dwellings, a number of which are nZEB compliant.

While the study uses data across the UK and Ireland it has relevance to a much wider context for the deployment of nZEB in Europe and housing globally, and in particular the provision of social housing.

Keywords nZEB, passive house, passivhaus, ventilation, Post Occupancy Evaluation, Social Housing, IEQ, financial analysis, cost of construction.

Nomenclature

BER	Building Energy Rating
B Reg	House designed to building regulation standard
DEAP	Dwelling Energy Assessment Procedure
DHW	Domestic Hot Water
EPBD	Energy Performance Building Directive
IoT	Internet of Things
IEQ	Indoor Environmental Quality
PH	Passive House
PHPP	Passive House Planning Package
POA	Post Occupancy Analysis
nZEB	Nearly Zero Energy Buildings
MVHR	Mechanical Ventilation with Heat Recovery
VAT	Value Added Tax

1. Introduction

Building standards have improved in the EU over the past number of decades, due to improved regulation and construction methodologies. This progression is soon to culminate in the imminent introduction of the nearly Zero Energy Building (nZEB) standard on a pan-European basis (EU, 2016a). As the industry across EU member states now focuses on reducing energy demand, the EU Commissioner has requested that appropriate strategies dealing with Indoor Environmental Quality (IEQ) be implemented in conjunction with nZEB deployment (EU, 2016b).

There is a wide range of strategies to design and build low energy or nZEB housing (as reviewed by Moran et al. 2017). The Passive House (PH) methodology is a well-established and clearly defined strategy for achieving low energy housing in various climates (Feist and Werner, 1994; Schnieders et al 2015; Mirela et al 2017). Essential to this, and most strategies, is minimising the space heating requirement via a highly insulated and airtight thermal envelope. National building regulations are becoming increasingly stringent in the specification of fabric performance. Given that insulation levels specified in national building regulations have now increased to those approaching the PH standard and airtightness is increasingly being identified as a means of reducing energy consumption and improving IEQ, two of the key tenets of the PH methodology are being mandated across EU member states. Similarly, the incorporation of renewables, also a key tenet of the Passive House Plus and Passive House Premium standards, is now also commonly required by building regulations. An investigation into the potential for wide roll out of the PH standard across a wider range of housing is timely in this context.

The energy efficient performance of the PH is well reported in the literature, with claims of up to an 80% reduction over traditional buildings in central Europe (Feist et al 2005; Schneiders et al 2006) and 62% reduction in heating energy consumption against modern homes on the island of Ireland (Colclough et al, 2017a). Studies are showing that the energy efficiency of the PH can vary and is strongly dependent on how they are operated by occupants, most particularly the chosen set-point room temperature (Wang et al 2017). In comparative studies, PH homes are shown to outperform low energy alternatives primarily due to a lower heating load claimed to result, to a large extent, from fewer window operations (Ridley et al 2014; Mahdavi and Doppelbauer, 2010). A key difference between the PH typology and other low energy building alternatives is the typical deployment of tempered air provision through Mechanical Ventilation with Heat Recovery (MVHR). In contrast, traditional housing built to the prevailing minimum building regulations in both the UK and Ireland commonly use through-wall, or trickle vents in windows to provide for fresh air. Although passive ventilation methods are flexible, forgiving and familiar - and therefore still remain popular amongst occupants - the provision of consistent and adequate air change is not always achieved or achievable. In a past study (Kinnane et al. 2016a) it was shown that passive/background ventilation can result in prolonged periods of 'overventilation' when air ingress through background vents is far above controlled rates specified in ventilation related building regulations (Part F in Ireland and Great Britain). This is most typical in winter conditions when the air is cold and considerable auxiliary heating is required to offset the impact of the cold air ingress. This in turn can result in high energy costs for occupants – particularly exacting on people in social housing. During summer months social housing dwellings were shown to be under ventilated, with low levels of air moving through background, through-wall vents although this could be boosted through purge ventilation (Kinnane et al. 2016a). 'Underventilation' is similarly observed in other monitoring studies of UK social housing dwellings, in this case, with open trickle vents in which summer time CO_2 levels were commonly above 2000 ppm and peaking at over 3500 ppm in bedrooms (McGill et al 2015a).

Although a full-house MVHR system is generally assumed to provide for more consistent ventilation, there is a paucity of documented results. Additionally occupants often struggle to understand and operate these unfamiliar systems. Considering this, and the non-optimal operation, more research is required to evaluate IEQ conditions in the PH and particularly in the context of social housing where operational difficulty and poor IEQ have been reported as common (McGill et al 2015a). In a recent review Wang et al (2017) document the breadth of work that analyses the energy performance of PH but bemoan the lack of studies that investigate energy efficiency and IEQ in the same. Some comprehensive and prolonged studies have documented indoor temperature profiles in PH homes, while also reporting on CO_2 and humidity levels (McGill et al 2017) and have also documented overheating which is a growing concern in today's, and future, climates. Low energy housing, characterised by high levels of insulation and airtightness are particularly susceptible to overheating (Kinnane et al 2016b), and low energy housing in the UK with MVHR exhibit higher minimum and average summertime temperatures (McGill et al 2017). Similarly overheating has been reported in a number of other PH studies in southern (Fokaides et al. 2016) and northwestern European climates (McLeod et al., 2013, Colclough et al., 2017b). Such overheating can potentially lead to a growth in domestic air-conditioning, with greater capital and operational expenditure. Greater attention is therefore needed on the provision of adequate ventilation in PH houses and further study is needed to present solutions if this typology is to be proposed as a low energy solution for social housing.

The additional capital cost of building to the PH standard is often cited as a practical reason for instead using traditional building techniques. In the past PH required supplementary insulation and a unique ventilation system which added cost over other low-energy or standard building types (Audenaert et al 2008; Georges et al 2012). However, as building regulations have improved to stipulate lower U-values (i.e. more fabric insulation), and reduced thermal bridging, this cost discrepancy has reduced. For Austria and Germany a capital cost increase of 3-6% is documented in (Feist, 2018). However, there is a need for further and updated comparative case studies, against the updated nZEB building standards being rolled out throughout Europe.

By focusing on a selection of homes built to the PH standard (as well as others that are not), this paper examines whether satisfactory IEQ can be delivered alongside reduced operational costs in social housing when constructing, cost-effectively, to the PH methodology. It provides a case study of new semi-detached houses – the most common dwelling types in Ireland (45% of all houses) (Ahern et al 2013) – and a typical typology for current and future social housing all of which are to be built to nZEB standard.

Specifically the aims of this study include;

- Comparison of the indoor environmental conditions experienced, and perceived, by occupants in nZEB dwellings built to the PH standard against homes built to the minimum building regulations, thereby investigating any benefits for occupants of building to the PH standard while meeting the EU drivers of energy efficiency and optimum IEQ.
- Investigation of the capital cost of building nZEB compliant dwellings using the PH standard, compared with dwellings built using traditional construction approaches thereby investigating its potential as a cost-effective solution for the burgeoning social housing demand across the EU, and,
- Analysis of the real operational energy and costs of the case study PH homes thereby examining the potential of the nZEB PH in eliminating fuel poverty.

Although the case study dwellings are located in Ireland, the results of this paper can be extrapolated to a wider context, and are particularly pertinent in the European context given the planned pan-European deployment of the nZEB standard, the climate independent definition of the PH standard and the need to provide social housing throughout Europe, and the world at large. The performance of the case study dwellings is contextualised by comparing results from a broader study of over twenty dwellings in the UK and Ireland, half of which are constructed to the PH standard and half to the prevailing minimum building regulations in the respective jurisdictions.

2. Background

2.1 The housing sector

The definition, and proportion, of social housing varies across the EU. Social housing accounts for almost 10% of Ireland's 2 million houses and apartments (ICSH, 2013), and 17% of all UK homes (Department for Communities and Local Government, 2016). Of the planned 25,000 to 30,00 homes to be built annually in the Republic of Ireland to 2040, over the next 10 years 112,000 will be social houses, representing up to 45% of the building activity (Anon, 2018). Social housing, given that it is provided by the government, has the potential to signpost the way to provide high-quality, low-cost housing for the industry at large.

Occupants of social housing experience disproportionate economic pressures due to high, and ever rising, fuel costs. Social housing is often densely, and more continually, occupied due to higher unemployment rates and/or higher age profiles amongst occupants (Tabatabaei Sameni et al, 2015). The problem of fuel poverty is widespread in Ireland and the UK (DECC, 2015) particularly amongst the elderly in social housing (Webb et al, 2013). Many people live in unhealthy cold conditions in efforts to save on high costs of heating energy, particularly in substandard homes. Elderly or infirm occupants may have distinct requirements and preferences (Kinnane et al 2016b). These pressures can lead to poor indoor environmental conditions for occupants of social housing. The PH typology has the potential to provide comfortable thermal conditions, with consistent air change to enable high IEQ. Thus it has the potential to improve the indoor environments and efficiency of the social housing stock over the approach of continuing to deliver homes in the traditional manner, and using renewables to reduce the overall energy demand. In this context, the PH methodology has a unique contribution to make to social housing.

Overall, the housing sector in Ireland and the UK, and the essential players, are often much maligned. Today there is a considerable under supply of housing in high demand areas, resulting in a plethora of societal ills including widespread elevated house prices, high rents, high incidence of fuel poverty and considerable homelessness. The residential sector is a heavy consumer of energy. In Ireland, as in the EU at large, the residential sector accounts for an estimated 25% of all final energy consumed. In the UK this is as high as 30% (DCLG, 2015), with 62% consumed in space heating 27 million residential homes (Palmer and Cooper, 2013). Many countries across the EU are planning considerable new home construction including Ireland where 500,000 homes are planned for construction by 2040 (Anon, 2018). To abide by regulation, and achieve the nZEB standard, these homes will need to be designed as airtight, and highly resistant to thermal losses, thereby resulting in improved efficiency but with the risk of a range of unintended consequences if not designed and ventilated well (Shrubsole et al., 2014). Primarily there is a risk of poor air quality and a growing concern that new energy efficient construction types may be increasing the risk of overheating in today's (and future) climates (Mavrogianni et al., 2015), (Kinnane et al, 2016c).

2.2 Passive House and nZEB

Given the planned 2020 implementation of the near Zero Energy Building (nZEB) standard in Europe, an investigation of the well-established Passive House (PH) standard for social housing is apposite. While the nZEB standard is focused exclusively on energy use, the PH standard was defined on the basis of thermal comfort and IEQ, with these objectives simultaneously being met with low space heating demand and often with air based heating. While a number of publications have been written to investigate the potential for the Passive House standard in the Irish climate (e.g. Colclough, 2011; Clarke et al, 2014) and a number have considered net zero energy buildings, (Hernandez and Kenny, 2010, Goggins et al, 2016), few have investigated the potential for the PH standard to meet the newly defined nZEB standard in the European context, especially in the social housing context.

EU countries have assessment procedures designed for their own context and climate, with associated parametric input software. In the UK the Standardised Assessment Procedure (SAP), is used to determine the Energy Performance Certificate (EPC) for housing. Similarly in Ireland the Dwelling Energy Assessment Procedure

(DEAP) methodology is used to determine the Building Energy Rating (BER). Passive Houses are evaluated using the Passive House Planning Package (PHPP) (PHI, 2016). To comply with the Passive House standard, dwellings must consume less than 120 $kWh.m^{-2}.yr^{-1}$ of primary energy, as determined by the PHPP for *all* energy use in the building, based on *net* floor area (PHI, 2011). The nZEB standard in Ireland (to be finalised in 2019) requires that on average dwellings must consume less than 45 $kWh.m^{-2}.yr^{-1}$ for *regulated* loads (i.e. space heating, DHW, fixed lighting and ventilation), based on the *gross* floor area, (Department of Environment, Community and Local Government, 2012). It therefore appears that the nZEB standard is more stringent than the Passive House standard. However, this is not a like-for-like comparison, as regulated loads are only a fraction of total loads (e.g. 50%) and net floor area is a fraction of gross floor area (e.g. 90%) as outlined in Colclough et al 2017c for the case study dwellings (see section 3.2). The national BER rates buildings on a 15 point scale from A1 to G, where the primary energy usage ranges from <25 $kWh.m^{-2}.yr^{-1}$ for an A1 house down to >450 $kWh.m^{-2}.yr^{-1}$ for a G rated building for the regulated load only (i.e DHW, space heating, fixed lighting and ventilation). The PH standard (see Figure 1) require a high level of insulation, minimization of thermal bridges and mechanical ventilation with heat recovery to achieve A rated dwellings. As a result - when houses are constructed to the PH standard - cost increases typically occur in the thermal envelope substructure (predominantly due to under floor and foundation wrap insulation) and in the thermal envelope superstructure (increased insulation in the wall fabric and expenditure associated with airtightness membranes and works). Windows and external doors are generally triple glazed. The costs of building the case study homes (BER of A1) were compared to that of building to the prevailing minimum building regulation standards (BER of A3) in Colclough et al, (2017d).

3. Methodology

3.1 Monitoring Framework

The work presented in this paper forms part of a bigger, ongoing study that is undertaking long-term monitoring of nZEB and Passive House typologies and traditionally built homes across the island of Ireland. An IEQ repository is being developed via the ongoing monitoring project which to date has involved over 20 dwellings, and is utilised here to provide valuable insights into the performance of the case study dwellings in comparison to the other monitored dwellings in both the Republic of Ireland and Northern Ireland (UK) (Colclough et al, 2017a & 2017b). New dwellings are continually being added to the monitoring project and these will be the focus of future studies.

Name	nZEB?	Site	Building type	Windows	Construction Concrete/Timbe	TFA Size {m2}	BER/EPC Size {m2}	Completed Year	Ventilation	Airtightness (n50)
PH 1	no	A	2 storey Hse, Detached	Triple glazed	Timber Frame	144	158	2014	MVHR	0.6
BRegs 1	no	A	2 storey Hse, Detached	Double gazed	Block		329	2010	PIV	n/a
PH 2	yes	B	Bungalow, Detached	Triple glazed	Timber Frame	185	220	2013	MVHR	0.58
BRegs 2	no	C	2 storey, detached	Double gazed	Timber Frame		294	2014	Nat Vent	n/a
PH 3	yes	D	Bungalow, Detached	Triple glazed	Timber Frame	127	145	2011	MVHR	0.51
BRegs 3	no	D	2 Storey, Detached	Double gazed	Block		230	2013	PIV	n/a
PH 4	yes	E	Bungalow, Detached	Triple glazed	Timber Frame	216	247	2016	MVHR	0.58
BRegs 4	no	F	2 Storey, Detached	Double gazed	block		210	2016	MVHR	n/a
PH 5	no	G	Not complete							
BRegs 5	no	H	2 storey Hse, Detached	Double gazed	Block		246	2013	MVHR	n/a
PH 6	yes	I	Semi detached, 2 storey	Triple glazed	Timber Frame	93	102	2016	MVHR	0.4
B Regs 6	no	I	Semi detached, 2 storey	Triple glazed	Timber Frame		102	2010	MVHR	1.68
PH 7	n/a	J	Detached, bungalow	Triple glazed	Timber frame	171		2011	MVHR	0.54
B Regs 7	no	K	Detached, 2 storey	Double gazed	Block		172	1998	Nat Vent	7.2
PH 8	yes	L	Detached, 2 Storey	Triple glazed	Block	350		2005	MVHR	1
B Regs 8	no	M	Detached, 2 Storey	Double gazed	Timber frame		325	2004	Nat Vent	n/a
PH 9	n/a	N	Detached, 2 Storey	Triple glazed	Block	256		2015	MVHR	0.50
B regs 9	no	O	Detached, bungalow	Double gazed	Block		c170	2016	Nat Vent	n/a
PH 10	n/a	P	Detached, 2 Storey	Triple glazed	Timber Frame	238		2011	MVHR	0.5
B Regs 10	no	O	Detached, 2 Storey	Double gazed	Block		180	1996	Nat Vent	n/a
PH 11	yes	I	Semi detached, 2 storey	Triple glazed	Timber Frame	93	102	2017	MVHR	0.3
PH 12	yes	I	Semi detached, 2 storey	Triple glazed	Timber Frame	93	102	2017	MVHR	0.3

Table 1 Details of monitored dwellings

This paper presents results from twenty homes in total - 11 Passive Houses (PH 1 – PH 12, excl. PH 5), and nine houses constructed to the prevailing minimum building regulations in Northern Ireland and the Republic of Ireland (B Regs 1 – B Regs 9), see Table 1.

The study is a multi-faceted evaluation across a range of parameters including comfort and indoor environmental conditions (IEQ), energy consumption as well as construction and operation costs. Five-minute data is collected for all houses, stored in the cloud and retrieved as necessary, exploiting Internet of Things (IoT) technology. IEQ is monitored using the indoor and outdoor modules of the Netatmo Weather Station. Data includes: indoor air temperature; indoor relative humidity; indoor CO_2 concentrations; dwelling noise level; outdoor temperature; outdoor relative humidity; barometric pressure, with readings taken every 5 minutes. The monitoring equipment is all commercially available and records indoor temperature in the range 0°C to 50°C, and outdoor temperatures in the -40°C to 65°C both with an accuracy of ± 0.3°C. The unit uses an optical CO_2 sensor with a range 0 to 5000 ppm (accuracy ± 50 ppm or ± 5%, although this error range is likely wider in reality (possibly up to ± 250ppm)), The sensor automatically calibrates once per week, baselining at 400 ppm. A detailed quantitative analysis for the three nZEB dwellings is presented for the three month winter period and also the three-month summer period over which monitoring took place.

CO_2 concentrations are used as an indication of ventilation quality in buildings as per previous research (Clancy, 2011) and elevated levels have been shown to detrimentally affect performance in the work place (Sassi, 2017). The UK Health and Safety Executive state that the normal international safety limit is 5000ppm. In school buildings, as another example, CO_2 concentrations are not to average more than 1500 during the occupied part of the day, while occupants in a teaching space should be able to lower the concentration of CO_2 to 1000ppm (Building Bulletin 101). If the fresh air is supplied at a rate of 8 ls^{-1} per person, the CO_2 concentration will generally remain below 1000ppm. However, there is a paucity of guidelines or definite thresholds for CO_2 concentrations in dwellings.

The European standard for the ventilation of Non-Residential Buildings (EN 13779) focuses on achieving a comfortable and healthy indoor environment in all seasons with acceptable installation and running costs for ventilation equipment. It specifies the required filter performance in a system to achieve a good Indoor Air Quality (IAQ) taking into consideration the outdoor air. The outdoor air is categorised in 3 levels, from ODA 1 where the air is pure except for temporary pollution such as pollen (CO_2 concentration of 350ppm), ODA 2 (small towns where CO_2 is assumed at 400ppm), up to ODA 3 with high concentrations of both gases (CO_2 of 450ppm) and particles.

Given that CO_2 is proposed as a good indicator of effective ventilation, an established method for determining the IEQ of spaces with human occupancy is to specify the CO_2 above outdoor levels, with typical ranges for CO_2 levels indicating high to low indoor air quality. IDA 1 indicates High IAQ with $CO_2 \leq$ 400ppm above outdoor levels; IDA 2 Medium IAQ (400 – 600ppm above outdoor levels), IDA 3 Moderate IAQ 600 –1000ppm above outdoor levels and 4 Low IAQ (> 1000 ppm above outdoor air). Given the location of the three dwellings within a small town, the outdoor CO_2 concentration is considered to be 400 ppm, and based on the above, CO_2 concentration levels below 800 ppm are considered to yield IDA 1 category high IAQ, 800-1000ppm IDA2, 1000-1400ppm IDA3 and >1400ppm are considered low IAQ.

All dwellings are assessed for their internal temperatures including the risk of overheating, and a number of temperature "bands" established to facilitate comparison with prevailing building temperature thresholds and comparative monitoring studies from Ireland and the UK (Kinnane et al. 2016c, McGill et al. 2017). Minimum temperature thresholds are not set for the Passive House standard, or in the UK's Standardised Assessment Procedure (SAP) or in Ireland's equivalent Dwelling Energy Assessment Procedure (DEAP) software. Both DEAP and SAP propose a set temperature of 21°C in the living room and 18°C for the "rest of dwelling" i.e. outside the living area and both of these temperatures are threshold temperatures. Passive Houses are designed to have a uniform temperature of 20°C throughout and a temperature threshold has therefore been set at 20°C. There is no maximum temperature specified in the Republic of Ireland's DEAP software which is used to define the Building Energy Rating (BER) but a temperature of 24°C is required in the UK's Standardised Assessment Procedure (SAP), the software used to determine the Energy Performance Certificate (EPC) in the case of air-conditioned buildings and a temperature has therefore been set at 24°C. The Passive House standard requires that a temperature in excess of 25°C cannot occur for more than 10% of the time. The upper temperature is therefore set at 26°C.

A similar static definition of overheating that is widely used is that defined by CIBSE TM36 (CIBSE, 2005). It describes overheating as >1% of occupied hours over 28°C and >5% of occupied hours over 25°C. These definitions are often challenged by comfort researchers as definite temperature thresholds simplify the complexity of thermal comfort sensations and response mechanisms. The international standard ISO 7730 addresses thermal comfort not only on the basis of the recorded air temperatures but also includes the parameters of clothing, insulation, metabolic rate, mean radiant temperature, air velocity and relative humidity. Given the number of parameters involved, it is not possible to directly correlate temperature bands used in this paper with thermal comfort or discomfort, and for this reason, the *risk* of overheating, rather than *actual* overheating is assumed when temperatures go above 25°C.

3.2 Case study houses

Three houses in particular are focused on in this study (PH 6, PH 11 and PH 12) (see Table 1 and Table 2) in relation to indoor temperatures, carbon dioxide concentrations, construction costs and operational energy consumption and costs. The three dwellings are in the same development (located at Enniscorthy, Co. Wexford in the south east of Ireland) and hence experience the similar local climatic conditions. They were constructed to comply with the PH standard, and achieve a BER of A1, *i.e.* have a primary energy regulated load of less than 25 kWh/m^2/yr. Two of the passive houses are currently used as social housing (PH11 and PH12), while the third (PH6) is owner occupied. All houses have been monitored for at least a one-year period. However, it should be noted that monitoring of the first year of home operation is not always representative of long term building operation for a wide range of reasons including increased familiarity with systems and technologies, optimisation of space heating, but also in contrast, a tendency toward inefficiency due to a lack of maintenance, replacement of filters etc. This case study will be updated over coming years to monitor future changes in house performance with age.

Images of the dwellings are shown in Figure 1 and 3 and a more detailed summary of their characteristics is given in Table 2.

Figure 1. Case study nZEB homes built to Passive House standard.

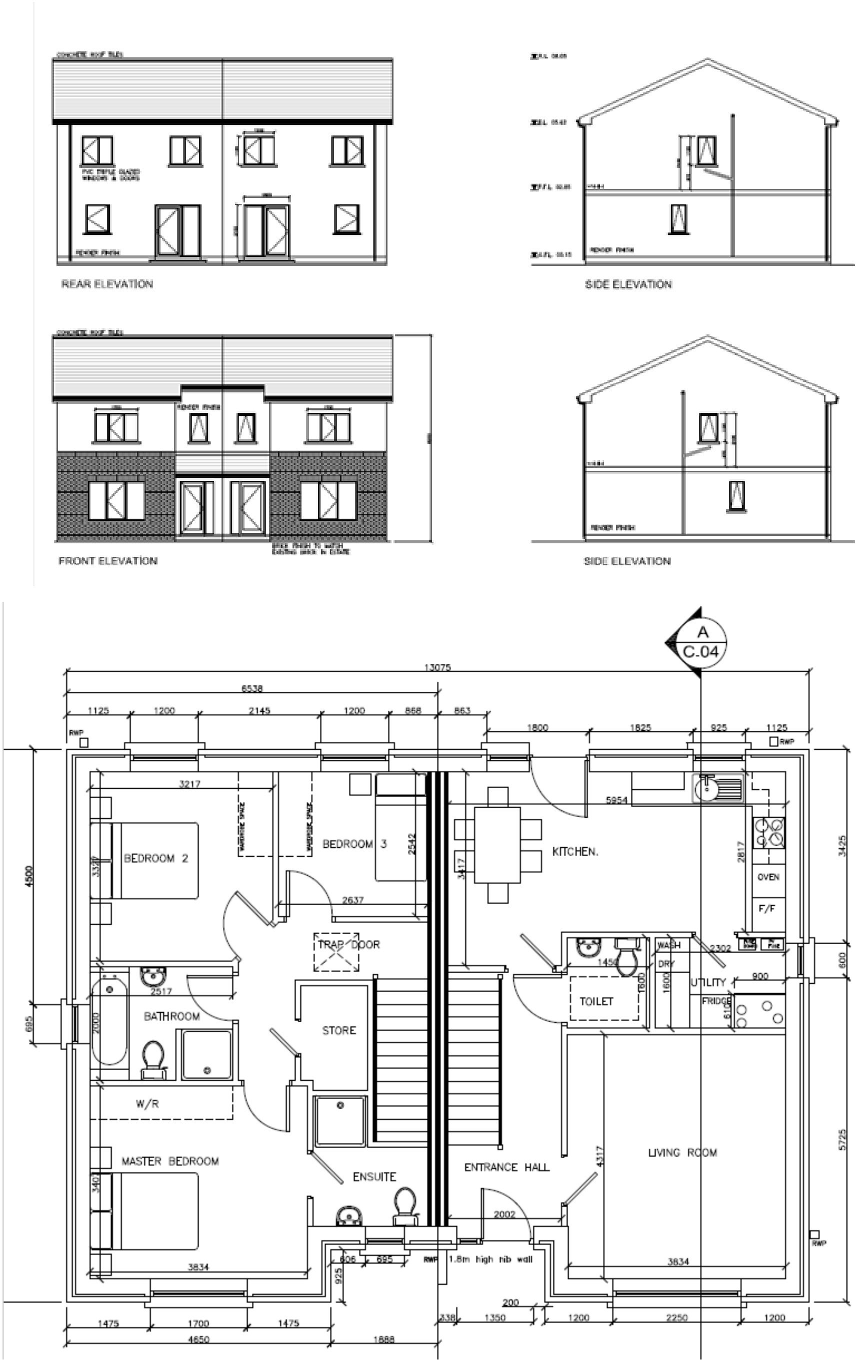

Figure 2. Elevations and ground floor plans of case study nZEB homes.

The houses studied are newly constructed two-storey timber framed semi-detached dwellings with triple glazed windows and Mechanical Ventilation with Heat Recovery (MVHR) systems (see Table 2). The MVHR (*Compact P* system) not only recovers heat from the expelled air, but also uses an integrated heat pump to provide Domestic Hot Water (DHW) and space heating (Nilan, 2018). Auxiliary and instantaneous space heating demand is met with two wall mounted 550 W electric radiators. The houses are almost identical in size and encompass a kitchen, living room and utility room on the ground floor and three-bedrooms (one en suite) and a bathroom on the first floor.

House Property		PH 6	PH 11	PH 12
Floor area (A_{floor})		102 m^2	102 m^2	102 m^2
Storeys		2	2	2
Occupants		1 adult	2 adults, 1 child	2 adult, 3 children
Construction	General	Semi-detached, timber frame, pitched roof. Constructed 2016.		
	Ceiling	U-value 0.07 W/m^2K. 500mm fibre rolled insulation		
	External walls	U-value 0.17 W/m^2K. 234mm Wall insulation		
	Ground floor	U-value: 0.08 W/m^2K. 230mm Insulation		
	Windows	U-value: 0.74 W/m^2K. Triple-glazed, argon filled.		
Chimneys/flues		no	no	no
Space Heating		MVHR HP & 2 electric radiators (550 W)	MVHR HP & 2 electric radiators (550 W)	MVHR HP & 2 electric radiators (550 W)
Ventilation system		MVHR	MVHR	MVHR
Solar system		5m^2 PV	5m^2 PV	5m^2 PV
Airtightness (ach @ 50Pa)		0.4	0.3	0.3

Table 2. Properties of the cases study houses.

Energy consumption is monitored using the Efergy Engage online monitoring system which gathers information on the energy consumption of the integrated HRV, overall electricity purchased, and electricity generated on site via the PV panels and uses IoT technology to upload the data to the cloud. A full year of energy consumption data is available for the single occupant, owner occupied, PH 6 for the calendar year 2017, and is available for the final six months of 2017 for the two family occupied social houses PH11 and PH 12.

An occupant survey is reported on which was undertaken in February 2018 for all three dwellings. This was a structured survey on both the building use and occupant response to thermal comfort and indoor environment proposed by McGill et al (2015b), with the scale set to abide by ISO7730 (2005) for ease of comparison across studies.

Costs are compared on an Element by Element basis using the National Standard Building Elements and Design Cost Control Procedures (NIPPCR 1970) format and are based on a scheme of 12 identical houses, within the set of 21 houses analysed in this study. The costs have been prepared by the builders' quantity surveyor, and an independent quantity surveyor, and are reported on in detail in Colclough et al (2017d).

4. Results

4.1 Overview

The subsequent sections present results of seasonal Indoor Environmental Quality (IEQ), energy consumption, construction and operational cost analysis, focusing on the three case study dwellings (PH6, PH11 and PH12), and using the larger dataset for specific analysis of CO2 concentrations in the bedrooms. Results are first presented for the three months of the winter period, and subsequently for the three months of the summer period. Bedroom CO2 concentrations are presented for all monitored dwellings. Construction costs for the case study dwellings are then presented and finely operational costs and energy consumption are reported on.

4.2 IEQ in Passive Houses. Winter Conditions.

For evaluation of indoor conditions during winter months in the case study dwellings, monitored temperatures documented in Figure 3 and Table 3 can be read in association with the occupant survey, documented in Tables 4 and 5. Together they offer insight into the range of operational conditions for similar homes and the subjectivity of occupant thermal comfort. Figure 3 shows that interior temperatures are similar for PH11 and PH12 which are occupied by a family of four, and a family of five respectively but are considerably different in PH6 – a singly occupied home. The monitored indoor temperatures can be correlated with the subjective preferences of the occupants reported in Table 5. Although all homes include occupants who report satisfaction with indoor temperatures, these temperatures vary considerably. While Indoor temperatures are consistently high in PH 11 (mean 22.2°C) and PH 12 (mean 22.3°C), cooler temperatures prevail in the livingroom (19.5°C) and bedroom of PH 6 (mean mean 16.5°C). The Living Room temperatures predominantly reside in the 21°C to 24°C bracket for PH 11 (72% of the time) and PH 12 (81% of the time), while PH 6 exhibits temperatures which are below the PH set temperature of 20°C for 62% of the time.

Similarly the bedroom temperatures in PH 11 and PH 12 are over the passive house set temperature of 20°C for 100% of the time (and within 21-24°C for 83% of the time and 87% of the time respectively), while the bedroom of PH 6 is continuously below 20°C. Evidently the occupant of PH 6 house prefers cooler indoor temperatures and records that overall the house is neither too hot or too cold during the winter period (although reporting that the bedroom is sometimes too cool). Kitchen temperatures in all dwellings show greater correlation, with temperatures in PH 6, PH11 and PH12 predominantly in the 21°C to 24°C bracket (93%, 74% and 93% of the time respectively).

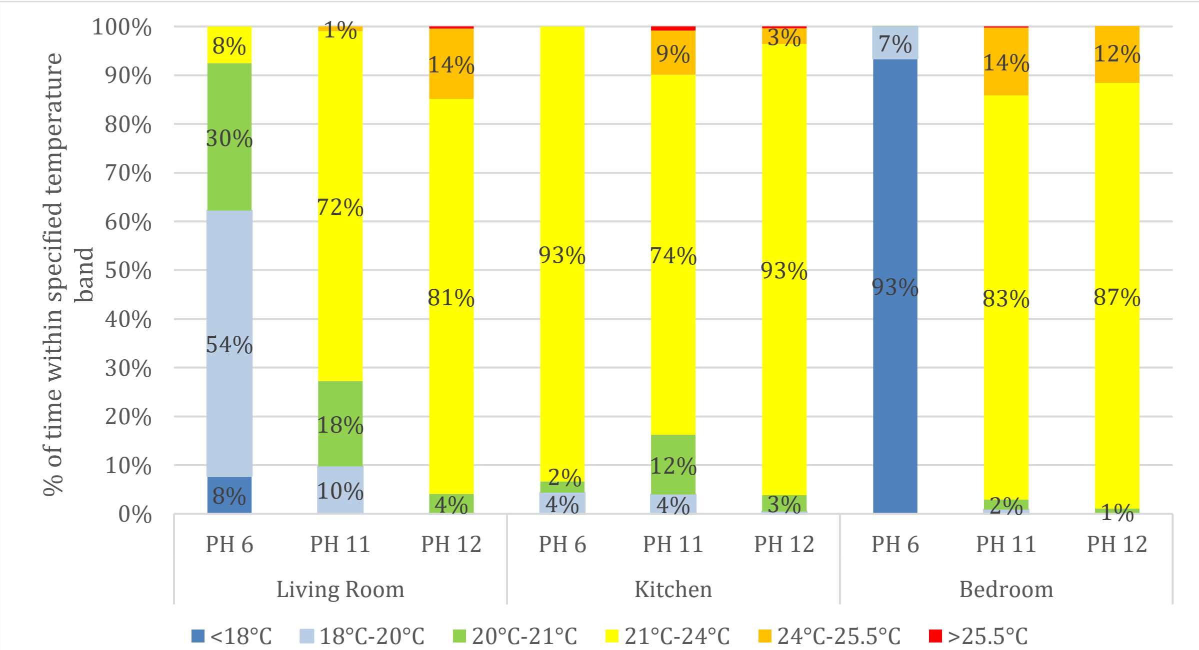

Figure 3. Winter temperatures in the living room, kitchen and bedrooms presented as a percentage of time within specified temperature bands.

Metric {°C}	Livingroom Temperature			Kitchen Temperature			Bedroom Temperature		
	PH 6	PH 11	PH 12	PH 6	PH 11	PH 12	PH 6	PH 11	PH 12
Mean	19.5	21.4	22.6	20.0	22.2	22.2	16.5	22.9	23.0
Max	22.1	24.6	26.8	23.9	31.6	28.0	19.1	26.2	26.7
Min	17.1	17.1	18.2	18.5	19.0	19.8	14.6	18.5	20.4

Table 3. Winter Temperature bands and Max Min and Mean temperatures

The occupants report that the bedroom temperatures in all three houses are sometimes cooler than desired, and this is corroborated by the monitoring study (Table 3 and Figure 3). Further exploration of the building in operation led to this phenomenon being attributed (by the ventilation equipment supplier) to the relatively long ventilation duct runs to the bedrooms. Thus while heat is being transferred inside the building by the ventilation system, a significant portion of the heat has been dissipated by the time the air reaches the bedroom.

How would you describe thermal comfort conditions in winter?						
Criteria	PH 6 Adult 1	PH 11 Adult1	PH 11 Adult 2	PH12 Adult1	PH12 Adult 2	Mean
Comfortable (3) /Uncomfortable (-3)	1	3	1	3	3	2
Too hot (3) / Too Cold (-3)	0	0	0	0	2	0
Stable (3) / Varies (-3)	1	3	3	0	3	2
Satisfaction (3), Dissatisfied (-3)	2	3	3	3	2	3

Table 4. Winter thermal comfort results from the occupant survey.

How would you describe air quality in winter?						
Criteria	PH 6 Adult 1	PH 11 Adult 1	PH 11 Adult 2	PH12 Adult 1	PH12 Adult 2	Mean
Dry (3) / Humid (-3)	2	-1	0	n/a	0	0
Fresh (3) /Stuffy (-3)	3	1	0	n/a	1	1
Odorless (3) / Oderous (-3)	1	3	0	n/a	3	2
Too Still (3) / Draughty (-3)	2	0	0	n/a	-1	0
Satisfied (3) Dissatisfied (-3)	2	3	3	n/a	3	3

Table 5. Winter air quality results from the occupant survey.

An occupant satisfaction survey was carried out in respect of thermal comfort and perceived indoor air quality, both for the winter period and the summer period. The internationally accepted ISO 7730 seven-point scale was used for each of the criteria, e.g. Hot ranging from 3, 2, 1 through neutral (0) to -1, -2, -3 (Cold). Overall satisfaction levels with both perceived comfort conditions (Table 4) and IEQ (Table 5) are exceptionally high rounding to 2 and 3 in both cases respectively (where 3 represents total satisfaction and -3 total dissatisfaction).

Also of note is the perceived thermal comfort condition which is described as neither too hot nor too cold by all occupants (apart from adult 2 in PH 12 who considers the home slightly too warm).

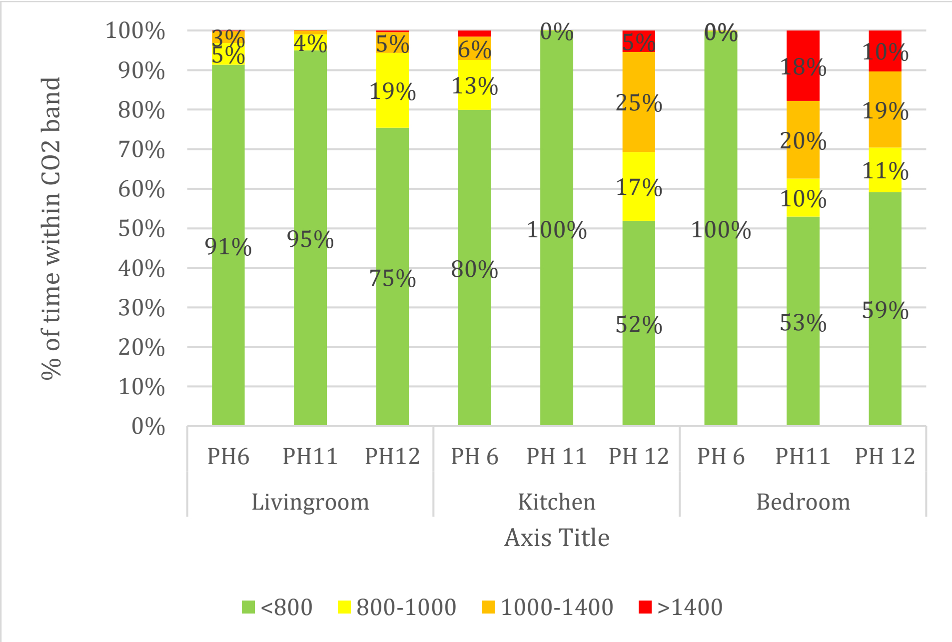

Figure 4. PH 6, PH 11 and PH 12 winter carbon dioxide levels in living room, kitchen and bedroom

Figure 4 shows that the carbon dioxide levels are within IDA1 limits (800 PPM) for the majority of the time. Overall the kitchens are below this threshold for 80% of the time, with PH 12 requiring further assessment given that it exceeds 1000 PPM for 30% of the time, and exceeds IDA4 (1400 ppm) for 5% the time. The bedrooms with dual occupancy exceed the IDA2 1000 PPM threshold for 38% of the time (PH11) and 29% of the time (PH12) whereas single occupancy bedroom remains below this threshold. Considering that the bedrooms are occupied for only one third of the time, average CO_2 concentrations exceed the 1000 PPM threshold for the majority of the occupied time.

To understand the monitored performance of these three identically designed and sited PH dwellings in the context of (a) a wider set of PH dwellings on the island of Ireland, and (b) the wider set of dwellings in general, the three PHs (PH6, PH11 and PH12) are shown in Figure 5 in relation to all houses being monitored. Occupancy was confirmed for the dwellings based on the noise levels and carbon dioxide concentrations to ensure the bedrooms were occupied for the period analysed. Data is presented in a range of formats including histograms and whisker charts. The histograms document the percentage of time the houses operate within certain temperature bands. In the whisker charts the median is represented by the **x** in the box. The maximum and minimum values (Q0 and Q4) are represented by the whiskers. If the data contains values that are greater than 1.5 times the interquartile range (i.e. 1.5*(Q3-Q1)) above Q3 or below Q1, they are displayed as outliers with the whiskers extending to a maximum of 1.5 times the interquartile range.

Bedroom CO_2 concentrations are shown for a single night - midwinter's 21st of December between midnight and 7 AM. They vary considerably between the set of PH dwellings (mechanically ventilated) and the houses built to minimum building regulations (naturally ventilated, apart from BReg 3 which uses positive input ventilation).

The monitoring of the dwellings took place during the winter of 2016/17 (Northern Ireland properties), and the winter of 2017/18 (Republic of Ireland properties).

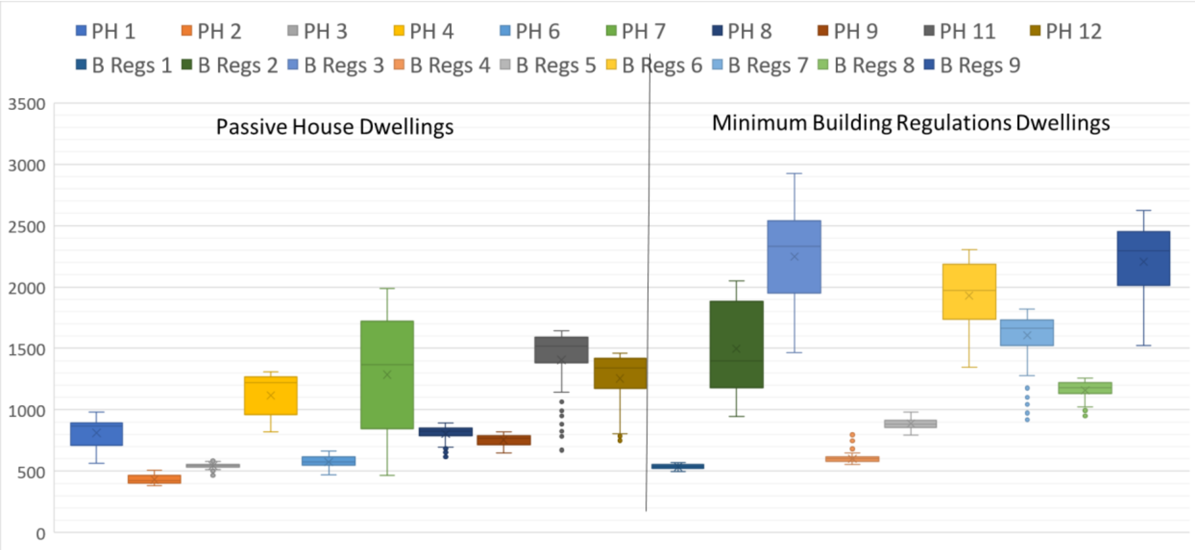

Figure 5 Winter solstice night time CO_2 concentrations across all monitored dwellings

Figure 5 shows the maximum, minimum, mean, top quartile and bottom quartile CO_2 levels. Real-life conditions affect the presented data and significant variations can be found in the CO_2 levels due to ventilation (whether natural or forced), occupancy, and whether the doors and windows are open or closed. However, overall it is seen that the mean and range of the CO_2 concentrations are lower in the houses constructed to the PH standard, compared with those constructed to the prevailing minimum UK (B Reg 1-5) or Republic of Ireland (B Reg 6-9) building regulations. Both PH 11 and PH 12 exhibit high CO_2 concentrations relative to the other passive houses, in line with dual occupancy and relatively small master bedrooms. The CO_2 concentrations in PH 11 and PH 12 are lower than the majority of the houses built to the minimum building regulations.

4.3 IEQ in Passive Houses. Summer Conditions.

Figure 6 shows the percentage of time occurrence of temperatures within defined temperature bands during the summer in the living room, kitchen and bedrooms for PH 6, PH 11 and PH 12. As was the case during the winter, the temperatures recorded in PH 6 are consistently lower than those in PH 11 and PH 12.

Of particular note with regard to the risk of overheating: it can be seen that the living room recorded temperatures over 24°C for 64% of the time (PH12), and 35% of the time PH 11. Similarly, the bedroom temperature was greater than 24°C for 62% of the time (PH 11) and 31% of the time (PH 12).

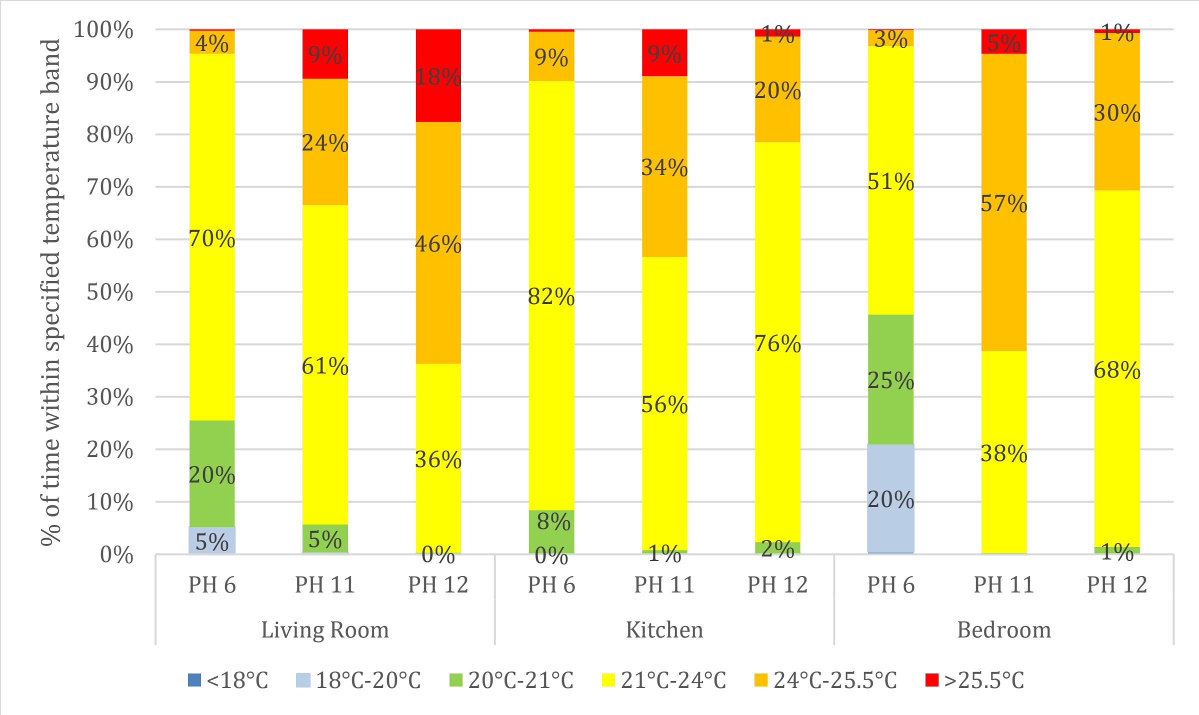

Figure 6 Summer temperatures in the living room, kitchen and bedrooms presented as a percentage of time within specified temperature bands.

Table 6 compares the mean, maximum and minimum temperatures in the living room, kitchen and bedroom, and presents data for the average living room and bedroom temperatures across all passive house dwellings.

Metric {°C}	Livingroom Temperature			Kitchen Temperature			Bedroom Temperature		
	PH 6	PH 11	PH 12	PH 6	PH 11	PH 12	PH 6	PH 11	PH 12
Mean	21.8	23.3	24.3	22.3	23.8	23.0	21.1	24.3	23.5
Max	25.9	27.2	29.2	26.0	33.8	27.2	27.0	27.7	26.7
Min	18.7	18.7	19.2	20.1	20.6	19.8	17.7	19.7	20.4

Table 6. Summer Temperature bands and Max Min and Mean temperatures

The mean living room temperatures in PH 11 and PH 12 are 23.3°C and 24.3°C, while it is seen that PH 6 is averaging 21.8°C over the summer. Thus, PH 11 and PH 12 (in particular) are seen to exhibit relatively high temperatures in comparison to the mean summer temperatures recorded (Colclough et al, 2017b) for the Northern Irish houses complying with the minimum building regulations (20.4°C), and those complying with the PH standard (21.6°C). The maximum temperature of 33.8°C recorded in the kitchen of PH 11 was recorded over a 30 minute period from 9:32 AM on 18th June, during a period when outdoor temperatures were 25°C. CO_2 levels and temperatures reduced rapidly after 10 AM, indicating that windows or the patio doors were opened at this time. Kitchen temperatures in excess of 30°C occurred at about the same time on the three subsequent days, after which time temperatures occasionally spiked above 26°C.

How would you describe thermal comfort conditions in summer?						
Criteria	PH 6 Adult 1	PH 11 Adult1	PH 11 Adult 2	PH12 Adult1	PH12 Adult 2	Mean
Comfortable (3) /Uncomfortable (-3)	-1	3	-1	-2	-3	-1
Too hot (3) / Too Cold (-3)	2	0	0	2	3	1
Stable (3) / Varies (-3)	-1	3	3	-1	-1	1
Satisfaction (3), Dissatisfied (-3)	1	3	3	-1	-2	1

Table 7. Summer thermal comfort results from the occupant survey.

Table 7 shows that on average the occupants scored the dwelling only slightly too warm during the summer (a score of 1, where 3 represents too hot and -3 represents too cold. The houses were scored -1 on average for comfort, where 3 is the highest score for comfort and -3 is the lowest score (uncomfortable). Significant variations are found, with the occupants of PH 12 considering the house uncomfortable (scores of -2 and -3) and too hot (2 and 3). While the average overall satisfaction scores 1 (where 3 is best and -3 is worst), again considerable variation can be found, with the occupants of PH 11 being totally satisfied, and the occupants of PH 12 scoring -1 and -2.

As shown in Table 8, on average, overall satisfaction levels with the air quality were good (scoring 1, where 3 represents satisfied and -3 represents dissatisfied), with the indoor air described as too still rather than draughty (overall score of 2, where 3 represents too still and -3 represents draughty).

How would you describe air quality in summer?						
Criteria	PH 6 Adult 1	PH 11 Adult 1	PH 11 Adult 2	PH12 Adult 1	PH12 Adult 2	Mean
Dry (3) / Humid (-3)	2	0	-2	n/a	-3	-3
Fresh (3) /Stuffy (-3)	1	-1	2	n/a	-3	-1
Odorless (3) / Oderous (-3)	1	3	0	n/a	3	2
Too Still (3) / Draughty (-3)	2	2	0	n/a	3	2
Satisfied (3) Dissatisfied (-3)	2	2	3	n/a	-1	1

Table 8. Winter air quality results from the occupant survey.

Figure 7 shows that CO_2 concentrations are considerably lower in the summer compared with the winter (Figure 4), and below the high IAQ (EN 13799) limits of 800 PPM for the majority of the time. Again the bedroom of PH 12 is higher than desired, although significantly lower than that experienced during the summer.

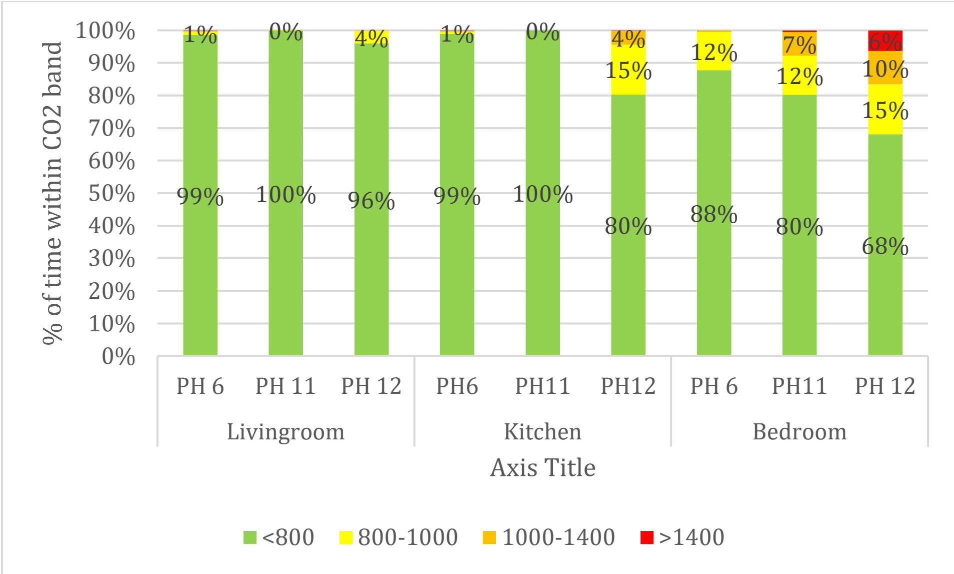

Figure 7. PH 6, PH 11 and PH 12 Summer carbon dioxide levels in bedroom, kitchen & living room

Figure 8 allows comparison of the summer solstice CO_2 concentrations with those experienced during the winter solstice (Figure 5). The monitoring of the dwellings took place during the summer of 2016 (Northern Ireland properties), and the summer of 2017 (Republic of Ireland properties).The summer CO_2 concentrations are considerably lower for PH 11 and PH 12, compared with the winter readings most likely due to increased purge ventilation. The occupant survey indicated that during the summer, windows are “regularly” or “occasionally” opened during the day in PH 6, and “regularly” opened in PH 11 and PH 12 during the day. The windows are “rarely” opened at night in PH 6, and “never” open at night in PH 11 or PH 12. PH 11 and PH 12 are seen to have significantly lower CO_2 concentrations compared with all but one of the houses built to the minimum building regulations, while PH 6 is exhibiting readings above all but one of the passive house dwellings, and in line with the best of the dwellings built to the minimum building regulations.

Although the preceding images show a clear benefit in designing nZEB social housing to PH standard, there is evidence of seasonal variation and outliers where both indoor temperatures and CO2 values are high. Anecdotal, but worthy of note, in the occupants satisfaction survey is the improvements in health reported by the tenant in PH 11 regarding their son who is an asthma sufferer. They reported that he hadn’t suffered an asthma attack since he moved into the PH. This was reported to be in stark contrast to his frequent use of a nebuliser in previous years, in a previous standard build house type. Similar feedback was given by another asthma sufferer in one of the eight houses used for social housing purposes.

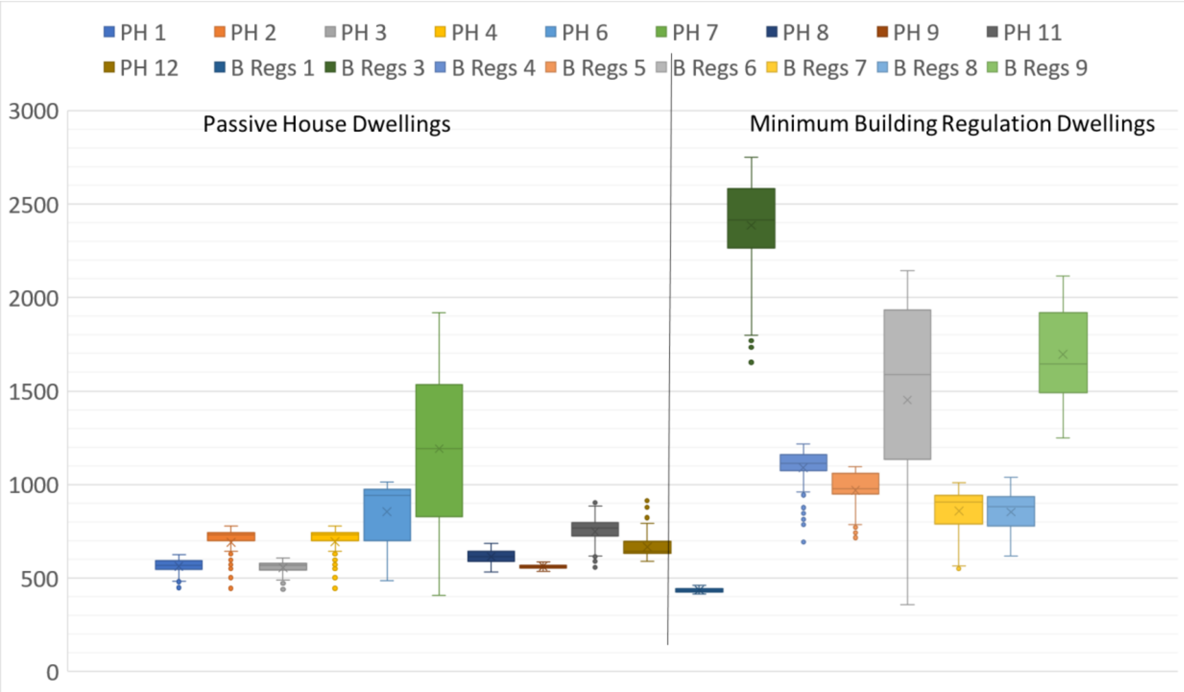

Figure 8 Summer Solstice night time CO_2 **concentrations across all monitored dwellings**

4.4 Costs

There are often concerns that the cost of building to low energy standards far exceeds building in a more traditional manner. This section examines the cost analysis performed in collaboration with the developer (based in the South East of Ireland) to inform his decision on whether to change his typical market offering (a home build to the current minimum building regulations including a traditional heating system) to a certified PH which is nZEB compliant (which has a lower space heating demand and a lower cost heating system). The analysis also considers the energy consumption and associated operational costs.

4.4.1 Capital Costs

The analysis gives an overview of the cost differential of constructing the case study dwellings to the nZEB standard using the PH methodology (nZEB/PH), and compares the cost differential of building to the current minimum Building Regulations (B Reg). It demonstrates that achieving the nZEB standard can be cost neutral compared with achieving the current building regulations in the Republic of Ireland.

The total cost of constructing the case study 102 m² dwelling to nZEB standard using the PH methodology is calculated to be €114,862. Costs are based on a designated date for the works of 1 January 2017, and exclude Value Added Tax (VAT) at the prevailing rates, cost of site purchase, and any design team or professional fees arising. This cost is considered the base cost in an analysis which calculates the cost of reverting to the traditional A3 standard dwelling market offering

.

Item	nZEB built to PH standard (PH)	A3 House built to minimum Building Regulation standards (B Reg)	extra(+) or reduced (-) cost B Reg home against PH
Thermal Envelope (substructure) {51.27m^2}	€6,923	€6,208	-€715
Thermal Envelope (superstructure) {146.2m^2}	€12,108	€8,938	-€3170
Windows {17.36m^2} and External Doors	€11,850	€10,950	-€900
Ventilation and Heating	€9,838	€12,488	+€2650
Preliminaries (site overheads)	€3,800	€6,065	+€2265
Total Construction Cost	€114,862	€114,992	+€130

Table 9. Extra (+) and reduced (-) cost of constructing the same dwelling to the minimum Irish current building regulations (A3 standard) compared with nZEB (A1) standard built using the PH methodology

Table 9 gives a summary of the additional costs (+) and cost reductions (-) inherent in constructing the social house dwelling to the minimum building regulations (A3) standard compared with the base case of constructing to the A1 (nZEB) standard for the items which differ based on the building standard considered. The total construction cost (including the items not detailed in Table 9) for the nZEB compliant PH case study houses, is €114,992, €130 less than building the same house to meet the current minimum building regulations. Each of the elements itemised in Table 9 are detailed below.

Less insulation (80mm) is required in the floor and foundations of the A3 dwelling compared with the nZEB/PH, resulting in a cost reduction of -€725, while an additional cost of +€10 is required to reduce cold bridging between the chimney stack and ground in the design of the A3 dwelling, leading to the overall net reduction in cost of -€715 for the substructure of the A3 dwelling.

Similarly considering the external walls, the current building regulations require a less costly wall build up primarily due to the reduced thickness of insulation in the walls of the nZEB/PH house (saving €1,786). They also are built with less cold bridging detailing (saving €1,384), leading to a superstructure cost reduction of -€3,170. The cost of the external windows and doors lead to a cost saving of -€900 when constructing to the current building regulations rather than the PH, as double glazed windows, (at a cost of €3,300) are less costly than the triple glazed PH windows (at a cost of €4,200).

In contrast, the constructed nZEB/PH incorporates a combined MVHR unit with an integrated heat pump to provide domestic hot water and space heating via the air distribution mechanism, with backup space heating provided by two low-cost 550W electric radiators. Thus cost savings are achieved in the B Reg house by not having to provide two 550 watt heaters and a HRV system to meet the low space heating demand of 10 W/m^2 of the Passivhaus standard (-€8,538). Additional cost are incurred for the B Reg dwelling due to the chimney stack and associated plasterwork and capping (+€2,931); Mechanical ventilation (MV) is required in the B Reg houses - 5 fans (+€922); Extra costs are required for a Stove and Hearth (+€1,300) plus traditional heating system with associated wet radiators, oil fired burner and hot water cylinder (+€6,125); An electrician is required to wire the foregoing at (+€350); Builders work associated with the foregoing, i.e. trenches, boxouts, oil line, cradle, opes and plinth will carry a cost of +€775; A Carbon Monoxide alarm is needed in the B Reg dwelling to monitor emissions from the oil heating (+€85). Therefore overall, plumbing and heating requires an additional cost of +€2,650 to construct to the current market offering which complies with the current building regulations over the nZEB/PH dwelling. It is noted that the stove and hearth (€1300) provided in the A3 dwelling is not specifically required to meet the current building regulations. It is however inappropriate to provide it in the PH dwelling, as it would be oversized given the low space heating demand of the PH.

In addition, extra costs are incurred due to overheads associated with increased time on site for the B Reg dwelling compared with the nZEB/PH dwelling. Given that the B Reg dwelling requires increased tradesmen activity for the provision of a chimney, the installation of radiators in each room, and associated first and second fix activities for plasterers etc., project critical path analysis indicates that the B Reg dwelling takes one week longer to construct. The overhead costs associated with this delay (insurance, hire of scaffolding, site supervision etc.) result in increased preliminaries. The cost differences are detailed as follows: add cost of site overhead and preliminaries associated with an additional five day programme (+€2750), add planning contributions discount not available to B Reg unit +€225, omit cost of PHPP Fee -€540, omit cost of blower door test -€170, leading to a net additional cost to construct the B Reg unit of €2,265.

In summary there is a total extra capital cost of €130 to construct the previous market offering of the A3 dwelling (complying with current minimum building regulations), compared with building to the A1 (nZEB) standard using the passive house methodology.

It is noted that the case study considered above is for one house in a development of 12 dwellings, where economies of scale apply. Costs will vary with the specifics of other buildings and prevailing building regulations. However, from the analysis, it is evident that the fundamental PH principle of using air as the heat transport mechanism can be used to significantly reduce costs associated with simultaneously ventilating and providing space heating. Further, by exploiting advantages inherent in the optimised integration of DHW, space heating and ventilation in a customised product, a cost-effective solution has been deployed, obviating the need and additional cost of a traditional wet heating system.

4.4.2 Energy consumption and operational costs

4.4.2.1 Overview

While the capital costs associated with constructing the building to the nZEB standard are seen to be cost neutral, social housing tenants are particularly sensitive to running costs. Thus the operational costs associated with the DHW, space heating and ventilation energy consumption of the nZEB/PH is investigated based on energy consumption data for PH 6 which is available for the calendar year 2017.

The running costs of appliances are not considered as they are assumed to be the same for both the nZEB and A3 dwelling. (It is noted however that the PH standard requires the use of energy efficient appliances in order to comply with the 120 kWh/m^2/a primary energy demand). Also, the operation/maintenance costs are not considered, as the annual cost of replacing air filters in the A1 PH dwelling is assumed to be similar to the annual cost of servicing the oil boiler in the A3 B Reg dwelling. PH 6 uses electricity as its sole source of energy. Electricity is purchased and also generated on site via a PV solar array which is integrated into the domestic supply. Any electricity generated which is surplus to instantaneous demand is exported to the grid.

Figure 9 shows the integrated HRV energy consumption profile of PH6 and the electric radiator energy consumption, in addition to the external temperature.

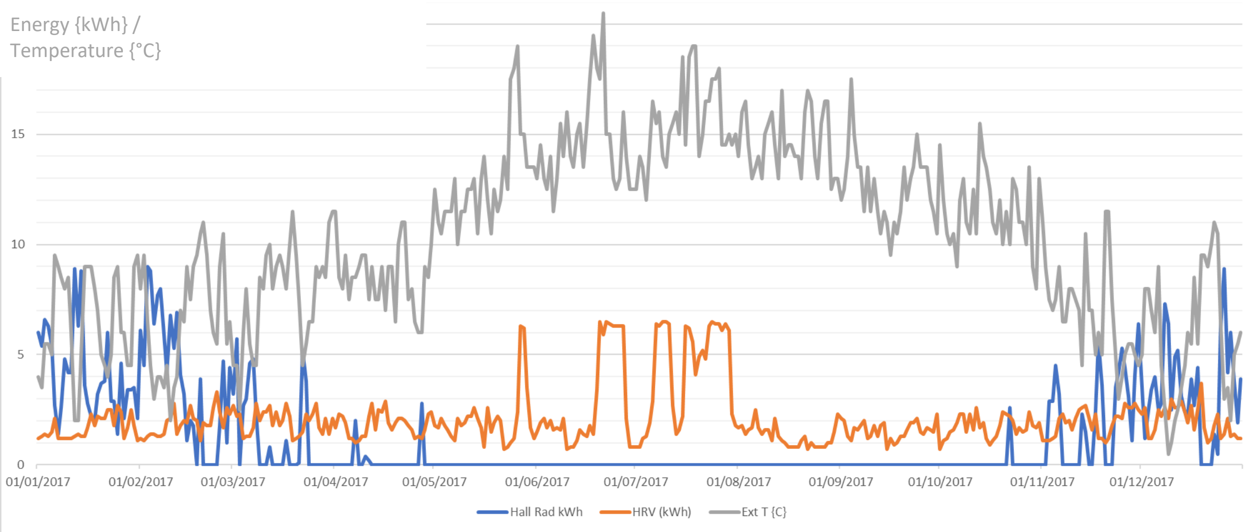

Figure 9. Heating and Ventilation Energy Consumption for a year of operation (2017) of PH 6.

The wall mounted radiators are seen to operate from the start of November to the end of March (apart from two individual usage occurrences in April and May). The daily electricity consumption of the MVHR unit averages 2.08 kWh/day and varies between 1.2 kWh/day and 3.3 kWh/day for the majority of the period, with notable increases (to approximately 6 kWh) during the summer months. This indicates that the majority of the space heating demand is being met by the electric radiators, and air cooling is taking place during the summer months. The extent of air cooling is difficult to specify, as the unit also provides DHW and ventilation. However, the unit consumes significantly more (i.e c.6 kWh) than the average daily load (of 2.09 kWh) on 31 days coinciding with the warm days in the summer. The extra energy consumption over the annualised average daily consumption of 2.09 kWh for the 31 days totals 117 kWh. If it is assumed that this is to provide space cooling, at the standard rate of 17.7 cents per kilowatt-hour, this equates to an approximate annual cost of €20.71.

4.4.2.2 Electrical energy consumption investigation

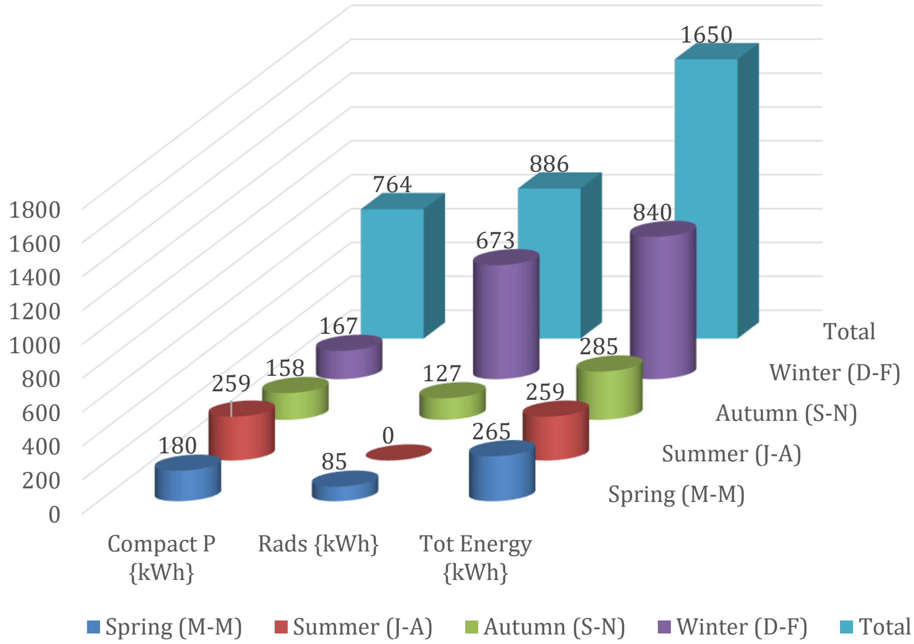

Figure 10. Distribution of Energy Consumption per season of 2017 of an nZEB/PH (PH6).

For the first year of operation (2017), the overall energy consumption for space heating, ventilation and domestic hot water totals 1650 kWh, comprising 886 kWh consumption from the radiators and 764 kWh of consumption from the MVHR and heat pump (Figure 10). During the spring, autumn and winter 180 kWh, 158 kWh and 167 kWh respectively are consumed by the MVHR and heat pump for ventilation, DHW and space heating via the air heating system. However, this figure is significantly higher (259 kWh) during the summer, corresponding with the cooling action of the unit (using the internal heat pump to reduce the air temperature). Also of note is the significant use of the electric radiators for space heating in PH6. In contrast initial analysis of the consumption in PH 11 and PH 12 demonstrates that the electric radiators have not been used, with the higher indoor temperatures being achieved solely with the use of the integrated heat pump and air heating. Given that the heat pump has a coefficient of performance in excess of 3, the radiator space heating demand of 886 kWh could potentially be reduced to less than 300 kWh through the adjustment of the heat pump settings. The total electricity purchased in 2017 amounted to 4334 kWh, and the total generated on site via the photovoltaic panels was 1210 kWh. Electricity produced on site and which is surplus to the instantaneous needs of the dwelling is exported to the grid. Therefore the total electricity used on site is less than the sum of the generated and purchase electricity (5544 kWh).

Energy	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2017
Purchased {kWh}	521	477	397	287	331	296	317	229	295	289	407	489	4336
Generated {kWh}	38	46	101	118	179	168	168	131	115	59	51	34	1210
Consumed {kWh}	554	516	479	386	477	422	433	330	388	339	449	518	5291
Exported {kWh}	6	7	19	19	34	43	52	30	21	9	10	5	255

Table 10. Breakdown of monthly electricity energy production and consumption in nZEB/PH (PH6)

Table 10 shows the amount of electricity which was generated on site (using the photovoltaic panels). It also shows the amount which was consumed in the dwelling, and exported to the grid.

The total amount consumed was 5291 kWh, of which 4336 kWh was purchased (equivalent to 82%). Thus only 82% of the electricity used in the dwelling was purchased. Given that the standard rate for electricity is 17.7c, the equivalent cost of a unit of consumed electricity is 17.7c multiplied by .82, or 14.5c.

Of the 1210 kWh generated by the solar panels, 255 kWh was exported to the grid, indicating that 955 kWh was used in the dwelling. It is noted that the Building Energy Rating (BER) produced for the dwelling predicted that 1020 kWh of electricity would be generated by the solar panels.

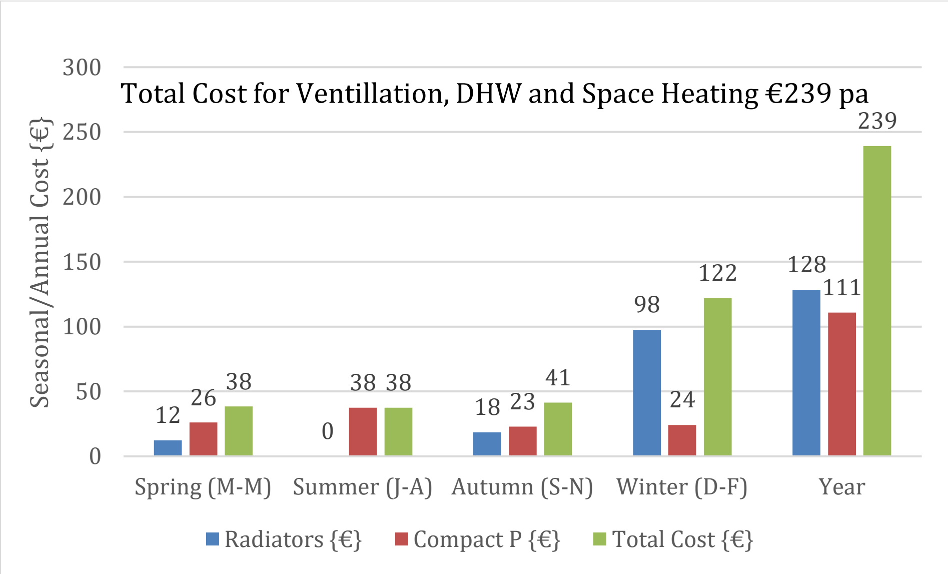

Figure 11. 2017 Costs for Ventilation, DHW and Space Heating

Figure 11 shows that the cost for Ventilation, DHW and Space Heating amounted to €239 over 2017 for the singly occupied dwelling. As previously stated, there are two electrical radiators which provide space heating in the hall and living room, in addition to the DHW, ventilation and air space heating provided by the Compact P unit. Due to the monitoring employed, it is not possible to isolate the consumption for space heating (i.e. the sum of the air space heating provided by the Compact P unit and the electric radiators). Based on as yet incomplete monitoring data for PH 11 and PH 12, which are occupied by families, the additional extra cost for heating and ventilation for family occupation equates to €192 leading to a total estimated cost for ventilation, DHW and space heating of €431 per annum for the families in the social housing dwellings.

An analysis of the electric appliance consumption in PH 12 revealed that c.€210 was being spent annually on the electrical consumption of the 20-year-old chest freezer, the highest cost of all appliances. The appliance was replaced at a cost of €202, reducing the annual costs to €27, saving in excess of €180 pa, equivalent to 23% of the annual spend on electric appliances, and representing a payback period of less than 14 months.

As part of the post occupancy analysis in PH 11, it was discovered that the PV solar array was not operating due to a commissioning error, this having resulted in the loss of 710 kWh, equivalent to €125.67 over the period. In the absence of the POA, this loss would have continued to accrue.

5. Discussion

5.1 Construction costs

Due to commercial sensitivity, it is very difficult to obtain accurate figures for the cost of construction of dwellings, and in particular for energy efficient dwellings which are not yet mandated. However, the Department of Housing, Planning and Local Government issued a Regulatory Impact Analysis (Department of Housing, Planning and Local Government, 2018) which estimated that the additional cost of meeting the nZEB standard varied between 0.9% and 2.9% (depending on the methodology employed) for a 126 m^2 semi detached dwelling, using established building practices. The presented case study demonstrates the business case of adding innovation by adopting the PH approach of reducing heating demand through a building envelope with high thermal and air tightness performance and therefore eliminating the traditional heating system. This is in accordance with recent theoretical analysis (Moran et al, 2017), which concluded that the key to achieving nZEB is high thermal resistivity and air tightness of building envelopes, key tenets of the PH methodology.

The benefits of using air as the heat transport mechanism via a combined heat pump and heat recovery ventilation system are seen to be twofold for the set of houses investigated in this study; heating costs are reduced (through the elimination of the traditional heating system), and forced ventilation provides a superior air quality (indicated by using CO2 as a proxy for air quality). The houses constructed to the existing minimum building regulations in contrast primarily use natural ventilation via trickle vents and/or through wall vents.

The PH dwelling does not have a stove and hearth, something which has traditionally been present in dwellings in Ireland and for which there may be an emotional attachment. However, given the heating requirements of nZEB/PH dwellings, the heat output for a single room is inappropriate and contributes to the lower cost of the nZEB/PH market offering. Other builders have adopted a similar approach and focused on "building the best building available" (Daly, 2017) thereby eliminating the cost of traditional elements such as radiators and solar panels resulting in cost a neutral PH market offering, according to the quoted independent quantity surveyor's report.

Cost comparisons in other European jurisdictions will vary not only due to local construction costs but also with existing building regulations and the local nZEB definitions. On the other hand, regions such as Brussels already mandate PH and high insulation levels and the use of renewables on residential buildings is common. There is a dwelling renewables requirement in the Republic of Ireland which does not apply for example in the UK, where mandated insulation levels are also less stringent. In addition, Brexit complications may impact on the implementation of nZEB and low-energy dwellings.

5.2 IEQ

Given the increased focus on ensuring adequate indoor air quality as industry focuses on delivering the low-energy demand mandated for nZEB compliance, the case study dwelling has demonstrated that the PH approach has the potential to cost effectively deliver both low energy demand and superior indoor air quality.

The monitoring data suggests that bedroom ventilation is an issue in homes built to the minimum building regulations, with significantly lower carbon dioxide concentrations experienced in the monitored certified passive house dwellings during both the summer and winter periods. The recorded CO_2 values are broadly in line with CO_2 levels recorded in low-energy and PH bedrooms in social houses in other studies (McGill 2015c), indicating the need to focus on ventilation strategies such as mechanical heat recovery and ventilation.

There is also anecdotal evidence of improved health outcomes with respect to asthma which is claimed by occupants two of the eight social housing dwellers since they moved into the PH, and further research needs to be done in this area to determine the underlying reason for this.

5.3 Temperature

The winter temperatures experienced in the PH dwellings vary, however, these temperatures were considered neither too hot nor too cold, and thermal comfort and indoor air quality overall satisfaction was exceptionally high during the winter. A notable exception to this was that the bedroom temperature in PH 6 and PH 12 were considered too low on some occasions which has been identified as a ventilation duct design consideration.

During the summer the temperatures in PH 11 and PH 12 were higher than PH6. Overall the houses were considered too warm during the summer by the majority of the occupants, (although the tenants in PH 11 consider the temperature neither too hot nor too cold and reported very high overall satisfaction).

Summer overheating is both a design and operations issue. It is noted that the bedroom windows were never opened at night in PH 11 and PH 12 even in summer, and rarely opened at night in PH 6. By availing of free night time cooling, the occupants could reduce the dwelling temperatures considerably, avoiding operation of the heat pump to provide cooling during the summer. Consideration should perhaps be given to passive stack ventilation, or shading, both measures which could reduce summer temperatures, thereby reducing the heat pump cooling energy consumption.

5.4 Operational Costs

Due to the very low annual heating cost, it is seen that the case study dwellings offer potential in the elimination of fuel poverty. For an individual on social welfare, illness benefit payment in Ireland (Dept Social Welfare, 2018) amounts to €198 per week, equivalent to €10,296 per annum. In such a case the annual heating and ventilation costs of €239 would account for 2.3% of household income, significantly below the 10% fuel poverty threshold defined by Boardman (1991). In the case of a family on jobseekers benefit with a partner and two dependent children, the benefit (Dept Social Welfare, 2018) is €198 + €138 + 2*31.8 = €399.6 per week, equivalent to €20,779 per annum. Based on monitoring conducted in PH 11 and PH 12, the estimated annual DHW and space heating cost of €431 pa represents 2.1% of total household income, again significantly below the fuel poverty threshold.

Post Occupancy Analysis of operational costs s identified the following savings in this study -

- space heating costs reduced by one third due to the use of the provided heat pump rather than radiators (configuration issue),
- commissioning issue with solar PV panels (710 kWh lost due to a commissioning error), equivalent to a loss of one €25 over the seven month period of nonoperation.
- replacement of an inefficient chest freezer representing an annual electricity consumption saving of €180 pa giving a payback of 14 months on the €202 cost (tenant education opportunity),

- 600 kWh cooling energy consumption could be eliminated e.g. by passive stack ventilation, shading or opening windows (design/operation).

POA also identified an issue with cooler than desired bedrooms, which could be addressed via redesign or insulation of duct run or provision of small electric radiator.

5.5 Energy Efficiency

There is a significant need to provide quality, low cost – to build – and low maintenance dwellings for the population. The holistic approach of the Passive House, where a MVHR is installed to provide ventilation guarantees a level of consistent fresh air to maintain occupant comfort, and good IEQ as demonstrated by reduced CO_2 levels in PH homes relative to naturally ventilated homes built to minimum building regulation standards. These later home types are today characterised by a reduction of air infiltration and hence an increased reliance on passive through-wall or trickle vents in windows to provide adequate air changes (Kinnane et al, 2016a). This strategy has to be questioned, if the aim is to maintain good IEQ as may be characterised by low CO_2 levels - at or below 1000ppm. The CALEBRE project (Loveday and Vadodaria (2013)) demonstrated that energy efficiency requires a considered approach and that retrofit of insulation and ventilation cannot be separated. This work also called for further research to understand the relationship between MVHR and airtightness in dwellings to establish the required air change rate to maintain indoor air quality. This paper has shown that the airtightness in new build is becoming an issue. As the thermal envelope is improved, so there should be a concentration on correct levels of ventilation – 8 ls^{-1} per person – if comfort conditions are to be maintained. The need for more post occupancy evaluation of dwellings – post retrofit and new build is illustrated clearly so that a clearer understanding of the indoor environmental quality may be obtained. Considering that this paper raises concerns about CO_2 concentrations in the bedroom at night, then next iterations of building regulations may need to move to specifying a ventilation flow rate per person instead of ventilator area size.

5.6 Further work

Given the small sample size, further work is required to monitor more dwellings not only to decrease the significance of sampling errors, but also to engage with a broader cross-section of occupants and obtain more occupant perspectives. The IoT has allowed the rapid deployment of monitoring equipment and the speedy retrieval of data. However, the stated accuracy of the CO_2 meters of ±5 percent is a limitation, and more accurate monitors such as a factory calibrated photoacoustic multi-gas monitor would ensure monitors provide detailed measurement of CO_2 levels. Given the findings in relation to bedroom CO_2 concentrations, and expected related improved health outcomes (e.g. asthma) a more detailed analysis should be performed on the indoor air quality, across a larger sample of dwellings. This should ideally be accompanied with an occupant diary indicating whether doors and or windows are open during the measurement period. Further engagement is required with tenants of the social houses to determine if there are any specific issues which need to be addressed e.g. with replacement of filters, operation of HRV system etc. Monitoring of a broader sample of low-energy / PH dwelling energy consumption would enable comparison against Building Energy Rating (BER) and PHPP predictions, therefore informing future development of the software.

6.0 Conclusions

While nZEB definitions vary from country to country within the EU, the case study highlights the potential in employing the PH design methodology for the cost-effective provision of nZEB compliant social housing. Referring to the aims outlined in the introduction of this study:

- Bedroom CO2 concentrations were seen to be significantly higher in dwellings with natural ventilation compared with the Passive Houses (with MVHR).
- IEQ of the PH dwellings is good with satisfaction levels of the case study houses scoring 3 in winter and 1 in summer where 3 is best and -3 is worst,
- While occupant satisfaction is high, potential areas for improvement include reducing interior summertime temperatures and enhancing control of bedroom temperatures,
- Care should be taken to ensure passive overheating safeguards are provided (e.g. adequate shading, passive stack ventilation), to reduce the risk of summer overheating and improve thermal comfort and reduce energy consumption for cooling,
- With regard to cost, nZEB compliant dwellings, when built to the PH standard, can be constructed at minimal additional cost over the cost of constructing traditional dwellings to current minimum building regulations,
- The nZEB dwellings, built to the PH standard, are characterised by low operating costs of less than €250 per annum for the combined costs of DHW, space heating and ventilation.
- Given the low running costs in combination with the good IEQ of the case study nZEB/PH dwellings, they might be assumed to provide a good typological solution for social housing. Such accommodation could make a significant contribution to alleviate fuel poverty and enable healthier environments.

The authors found that post occupancy engagement with occupants is key to exploiting the full potential of low-energy dwellings both from the technical perspective of ensuring correct operation of the dwelling and through education for the tenants to ensure they benefit fully from the design features. Further, the POA affords the opportunity to the developer to incorporate key learnings into future designs (e.g. shading and stack ventilation and design of ventilation duct runs). This information has been fed back by the research team to the design, construction and development team in an effort to disseminate key findings and ensure optimum development going forward.

By focusing on the monitoring of a selection of homes built to PH standard – in comparison to homes built to the minimum building regulations - this study found satisfactory IEQ can be delivered alongside reduced operational costs in social housing when constructing, cost-effectively, to the PH methodology.

Acknowledgements

The authors would like to acknowledge the contribution of proof readers, architects, homeowners and tenants who accommodated the project. Particular thanks are due to the developer and his quantity surveyor without whose assistance this analysis would not have been possible.

Funding

This work was supported by Enterprise Ireland (Republic of Ireland) and Invest NI (UK) through their innovation voucher scheme and the Interdisciplinary Centre for Storage, Transformation and Upgrading of Thermal Energy (i-STUTE) under EP/K011847/1.

Bibliography

AHERN, C., GRIFFITHS, P. and O'FLAHERTY, M., 2013. State of the Irish housing stock—Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock. *Energy Policy,* 55, pp. 139-151.

ANON, 2018. *National Development Plan 2018 - 2027.* http://www.gov.ie/en/project-ireland-2040/ edn. Dublin: Government of Ireland.

AUDENAERT, A., DE CLEYN, S.H. and VANKERCKHOVE, B., 2008. *Economic analysis of passive houses and low-energy houses compared with standard houses.*

BOARDMAN, B., 1991. Fuel poverty is different. *Policy Studies,* 12(4), pp. 30-41.

CIBSE, 2005. *TM36 Climate Change and the Indoor Environment: IMpacts and Adaptation.* ISBN 9781903287507 edn. London: CIBSE.

CLANCY, E., 2011. *Indoor Air Quality and Ventilation: CIBSE Knowledge Series: KS17.* CIBSE.

CLARKE, J., COLCLOUGH, S., GRIFFITHS, P. and MCLESKEY, J.T., 2014. A passive house with seasonal solar energy store: in situ data and numerical modelling. *International Journal of Ambient Energy,* (1), pp. 35-70.

COLCLOUGH, S., 2011. *Thermal energy storage applied to the Passivhaus standard in the Irish climate*, Ulster University.

COLCLOUGH, S., GRIFFITHS, P. and HEWITT, N.J., 2017a. Winter performance of certified passive houses In a Temperate Maritime Climate – nZEB Compliant? *Mediterranean Green Buildings and Renewable Energy Forum*, Jul 31 to Aug 3 2017a.

COLCLOUGH, S., GRIFFITHS, P. and COLCLOUGH, S., 2017b. Summer performance of certified passive houses In Temperate Maritime Climates, L. BROTAS, S. ROAF and F. NICOL, eds. In: *Design to Thrive: Proceedings Volume 3, PLEA 2017 conference, 3rd to 5th July 2017, NCEUB 2017. ISBN 978-0-9928957-5-4, pp. 385-386-392.*, 2nd-5th July 2017 2017b, NCEUB, pp. 3943-3950.

COLCLOUGH, S.M., O'LEARY, T., HEWITT, N.J. and GRIFFITHS, P., 2017c. The near Zero Energy Building standard and the Passivhaus standard – a case study, *Design to Thrive: Proceedings Volume 1, PLEA 2017 conference*, 3rd to 5th July 2017c, NCEUB 2017. ISBN 978-0-9928957-5-4, pp. 385-392.

COLCLOUGH, S., MERNAGH, J., SINNOTT, D., HEWITT, N.J. and GRIFFITHS, P., 2017d. The cost of building to the near Zero Energy Building standard – a financial case study, *Mediterranean Green Buildings and Renewable Energy Forum*, July 31 to August 3 2017d.

DALY, L., 2017, March 5. Take the Silken road*. The Sunday Times* Move, https://www.thetimes.co.uk/article/take-the-silken-road-0zgrmjksh.

DCLG, 2015. *House building in England: October to December 2014.* Gov.uk - Department for Communities and Local Government.

DECC, 27 July, 2017-last update, Digest of UK energy statistics (DUKES) [Homepage of DECC], [Online]. Available: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes [Feb 23, 2018].

DECC, 2015. *Annual Fuel Poverty Statistics Report.* London, England: UK Department of Energy & Climate Change.

DENNEHY, E. and HOWLEY, M., 2013. *Energy in the Residential Sector.* http://www.seai.ie/Publications/Statistics_Publications/Energy-in-the-Residential-Sector/Energy-in-the-Residential-Sector-2013.pdf. Dublin, Ireland: Sustainable Energy Authority of Ireland.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT, 2016. *English Housing Survey - Headline Report 2014 to 2015.* London, England: Department for Communities and Local Government.
DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT, 2014. *House building in England: October to December 2014.* https://www.gov.uk/government/statistics/house-building-in-england-october-to-december-2014: House building in England: October to December 2014.
DEPARTMENT OF ENVIRONMENT, COMMUNITY AND LOCAL GOVERNMENT, 2012. *Towards Nearly Zero Energy Buildings in Ireland, Planning for 2020 and Beyond .* Dublin: Department of Environment, Community and Local Government.
DEPARTMENT OF HOUSING, PLANNING AND LOCAL GOVERNMENT, 2018. *Proposed amendments to Part L and Part F of the Building Regulations and Technical Guidance Document L& F: Part L& F of the Building Regulations Part L (Conservation of Fuel and Energy) Dwellings and Part F (Ventilation).* Regulatory Impact Analysis (RIA) edn. Department of Housing, Planning and Local Government; Dublin: Republic of Ireland.
DEPT SOCIAL WELFARE, , Social Welfare Rates of Payment 2018 - SW19.
Available: http://www.welfare.ie/en/Pages/Jobseekers-supports.aspx [February 22, 2018].
EU, 2016a. *European CommissionDirective 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur. Communities, L 153 (2010), pp. 13-35. European CommissionDirective 2016 Annex 1 COM 860 Final.* EU Directive edn. Brussels: EU.
EU, 2016b. *COMMISSION RECOMMENDATION (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings, Section 2.1.1.* Recommendation edn. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016H1318#ntc8-L_2016208EN.01004801-E0008: EU.
FEIST, W., 2018. The passive house – a solution for affordable housing, W. FEIST, ed. In: *22nd International Passive House Conference 2018*, 9th to 10th of March 2018, Passive House Institute, pp. 69--81.
FEIST, W., SCHNIEDERS, J., DORER, V. and HAAS, A., 2005. Re-inventing air heating: convenient and comfortable within the frame of the Passive House concept. *Energy Build,* 37, pp. 1186-1203.
FEIST, W. and WERNER W, September 1994. *Energiekennwerte im Passivhaus Darmstadt: 11.9 (Heizung) + 6.1 (Warmwasser) + 2.6 (Kochgas) + 11.2 (Gesamtstrom) kW h/(m^2 a).* Passivhaus-Bericht Nr. 4 edn. Darmstadt: Institut Wohnen und Umwelt.
FOKAIDES, P.A., CHRISTOFOROU, E., ILIC, M. and PAPADOPOULOS, A., 2016. *Performance of a Passive House under subtropical climatic conditions.*
GEORGES, L., MASSART, C., VAN MOESEKE, G. and DE HERDE, A., 2012. *Environmental and economic performance of heating systems for energy-efficient dwellings: Case of passive and low-energy single-family houses.*
GOGGINS, J., MORAN, P., ARMSTRONG, A. and HAJDUKIEWICZ, M., 2016. Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland. *Energy and Buildings,* 116, pp. 622-637.
HERNANDEZ, P. and KENNY, P., 2010. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings,* 42(6), pp. 815-821.
ICSH, 2013. *Pre Budget Submission.* https://www.icsh.ie/content/publications/icsh-pre-budget-submission-2014: Irish Council for Social Housing.
KINNANE, O., SINNOTT, D. and TURNER, W.J.N., 2016a. *Evaluation of passive ventilation provision in domestic housing retrofit.*
KINNANE, O., GREY, T. and DYER, M., 2016b. Perceptions of thermal environments in dementia friendly dwellings, *Proceedings of 9thWindsor Conference: Making Comfort Relevant Cumberland Lodge, Windsor, UK, 7-10 April 2016. Network for Comfort and Energy Use in Buildings, http://nceub.org.uk* , 7th-10th April 2016b, pp. Volume 9.
KINNANE, O., GREY, T. and DYER, M., 2016c. Adaptable housing design for climate change adaptation, ISSN 1478-4629 and E-ISSN 1751-7680, eds. In: *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, October 2016
2016c, https://doi.org/10.1680/jensu.15.00029, pp. Volume 170 Issue 5, October 2017, pp. 249-267.
LOVEDAY, D. & VADODARIA, K., 2018-last update, Project CALEBRE, Consumer Appealing Low Energy technologies for Building Retrofitting, A summary of the project and its findings [Homepage of Loughborough University], [Online].
Available: www.lboro.ac.uk/microsites/enterprise/calebre/project-calebre-summary.pdf [02/28, 2018].
MAHDAVI, A. and DOPPELBAUER, E., 2010. *A performance comparison of passive and low-energy buildings.*

MAVROGIANNI, A., TAYLOR, J., DAVIES, M., THOUA, C. and KOLM-MURRAY, J., 2015. Urban social housing resilience to excess summer heat. *Build. Res. Inf.,* 43, pp. 316–333-doi:10.1080/09613218.2015.991515.
MCGILL, G., OYEDELE, L.O. and MCALLISTER, K., 2015a. *Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing.*
MCGILL, G., OYEDELE, L.O. and KEEFFE, G., 2015b. Indoor air-quality investigation in code for sustainable homes and passivhaus dwellings: A case study. *W J of Sci, Tech and Sus Dev,* 12(1), pp. 39-60.
MCGILL, G., OYEDELE, L., KEEFFE, G., MCALLISTER, K. and SHARPE, T., 2015c. BEDROOM ENVIRONMENTAL CONDITIONS IN AIRTIGHT MECHANICALLY VENTILATED DWELLINGS, *Healthy Buildings Europe*, 18-20 May 2015c, Available from http://radar.gsa.ac.uk/3679/1/McGill,%20Bedroom%20Environmental%20Conditions%20in%20Airtight%20Mechanically%20Ventilated%20Dwellings.pdf.
MCGILL, G., SHARPE, T., ROBERTSON, L., GUPTA, R. and MAWDITT, I., 2017. Meta-analysis of indoor temperatures in new-build housing. *Building Research & Information,* 45(1-2), pp. 19-39.
MCLEOD, R.S., HOPFE, C.J. and KWAN, A., 2013. *An investigation into future performance and overheating risks in Passivhaus dwellings.*
MIRELA, M., TANASIEV, V., DINCA, C., BADEA, A. and VIDU, R., 2017. Passive house analysis in terms of energy performance. *Energy and Buildings,* 144, pp. 74-86.
MORAN, P., GOGGINS, J. and HAJDUKIEWICZ, M., 2017. *Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate.*
NILAN, , Domestic Solutions - Compact P. Available: https://www.nilanireland.ie/domestic-solutions/compact-solutions/compact-p/ [02/28, 2018].
PALMER, J. and COOPER, I., 2013. *United Kingdom housing energy fact file.* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf: Department of Energy and Climate Change.
PHI, 2016-last update, Passive House Planning Package. Available: https://passipedia.org/planning/calculating_energy_efficiency/phpp_-_the_passive_house_planning_package.
PHI, 28 November 2011-last update, What is a Passive House?. Available: http://www.passipedia.org/passipedia_en/basics/what_is_a_passive_house [May 22, 2013].
RIDLEY, I., CLARKE, A., BERE, J., ALTAMIRANO, H., LEWIS, S., DURDEV, M. and FARR, A., 2013. The monitored performance of the first new London dwelling certified to the Passive House standard. *Energy and Buildings,* 63(0), pp. 67-78.
SASSI, P., 2017. Thermal comfort and indoor air quality in super-insulated housing with natural and decentralized ventilation systems in the south of the UK. *Architectural Science Review,* 60(3), pp. 167-179.
SCHNIEDERS, J. and HERMELINK, A., 2006. CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy,* 34, pp. 151-171.
SHRUBSOLE, C., MACMILLAN, A., DAVIES, M. and MAY, N., 2014. 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock. *Indoor and Built Environment,* 23(3), pp. 340-352.
TABATABAEI SAMENI, S.M., GATERELL, M., MONTAZAMI, A. and AHMED, A., 2015. *Overheating investigation in UK social housing flats built to the Passivhaus standard.*
WANG, Y., KUCKELKORN, J., ZHAO, F., SPLIETHOFF, H. and LANG, W., 2017. *A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings.*
WEBB, E., BLANE, D. and DE VRIES, R., 2013. Housing and respiratory health at older ages. *J Epidemiol Community Health,* 67(doi:10.1136/jech-2012-201458), pp. 280-285.